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POLYPROPYLENE FIBER REINFORCED CONCRETE FOR STORING NUCLEAR WASTE

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ABSTRACT

This study investigates the performance of Polypropylene fiber as reinforcement in a concrete matrix for the application of storage of radioactive nuclear waste. Concrete hollow vessels of M50 grade were prepared as a model of a storage tank for nuclear wastes. Various percentages of Polypropylene fibers (0.1%, 0.15%, 0.2%, by weight of concrete) have been taken into account to find out its effect on the permeability and shrinkage properties of concrete. Certain percentages of cementitious material were replaced by silica fumes in order to increase the resistivity of concrete cylinders. Homogeneity and resistivity of the concrete vessels were tested by the Ultrasonic Pulse Velocity test and the Four Probe Analyser test respectively. The test results have substantiated that the polypropylene fiber reinforced concrete vessels are suitable for holding radioactive waste. The test results have also verified that the reduction in the compressive strength of the concrete due to polypropylene fiber is negligible.

KEYWORDS: Polypropylene fiber, Silica Fumes, NUCLEAR waste, Permeability & Electrical Resistivity

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Original Article

1. INTRODUCTION

The usage of nuclear elements is expected to rise abruptly in near future owing to the high demand for energy and power. It is susceptible that the currently available facilities to manage radioactive waste may not be sufficient enough. Therefore, the disposal of nuclear waste will be of very much concerned in near future for the well-being in the day to day life. Since very long, the primary focus of nuclear waste storage research has been oriented toward host materials that can handle the large structural damage induced by the high-energy α-decay of actinides. However, by optimizing the vitrification process of actinides and repositories capacity, the investigation of other forms of containers specifically targeted at low- and medium-level waste has prompted. In case of any disaster such as Fukushima, large volumes of contaminated soils, water, and buildings had to be quickly handled. In such cases, the container becomes inevitable for storage[1].

Dumping of nuclear waste was considered as a helpful solution but it was observed that normal concrete matrix was insufficient to hold the radiations coming out from the radioactive wastes. This leads to the discharge of radioactive particles in the soil, nearby water bodies and the surroundings which ultimately leads to the depletion of entire aquatic, terrestrial ecosystem. Thus, there exists a need to make the concrete mix good enough so that no radioactive waste escapes through the micro defects present in the concrete. Traditionally, the virgin polypropylene fiber is used to make leak-proof concrete structures. From the literature [2-15], it was observed that the use of polypropylene fiber increases the binding capacity of the concrete matrix.

Control of cracks in the container plays an important role in radioactive waste management. Concrete containers need to be least permeable and consequently, there should be less risk of leakage. Cracks not only reduce the quality of concrete but also make structures out of service. Therefore, it is important to reduce the crack width and this can be achieved by adding polypropylene fibers to concrete. In this context, an attempt has been made to investigate the effectiveness of polypropylene fiber reinforced concrete in the storage of radioactive nuclear waste. Concrete hollow vessels of M50 grade were prepared as a scaled down model of a storage tank for nuclear wastes. Various percentages of replacement of Polypropylene fibers (0.1%, 0.15%, 0.2%, by weight of concrete) were studied to find out its effect on the permeability and shrinkage properties of concrete. Certain percentages of the weight of cementitious material were also replaced by silica fumes in order to increase the resistivity of concrete cylinders. The suitability of the containers was substantiated by performing relevant tests.

2. EXPERIMENTAL PROGRAM

2.1. Materials Used

2.1.1. Cement

Ordinary Portland Cement grade 53 conforming to IS 12269-1987 [16], supplied under the brand name of Ultra-Tech was used. The percentage of clinker and gypsum in the cement was 95–100% and 0–5% respectively, while the specific gravity was found to be 3.15.

2.1.2. Superplasticizer

Retarding superplasticizer based on Naphthalene Formaldehyde Sulfonate-based high-range water-reducing admixture (HRWRA) [17] conforming to IS 9103-1978 [18] with commercial name Naphthalene Sulfonate Formaldehyde Condensate was used as an admixture.

2.1.3. Aggregate

River sand (<4.75mm) having fineness modulus 2.397 and specific gravity 2.54 was used as fine aggregate. Crushed natural stone of size 20mm of specific gravity 2.77 and fineness modulus 7.07; and 10mm size of specific gravity 2.75 and fineness modulus 6.74 were used as coarse aggregate. The 10mm and 20mm aggregates were well graded in suitable proportion as per IS 383-1970 [19] and the ratio of 10mm to 20mm aggregate was 3:1. The coarse aggregate used in this investigation was thoroughly washed and air dried to exclude the dirt and water from its surface.

2.1.4. Silica Fumes

Silica fumes conforming to IS 15388-2003 [20] was used in the study. More than 95% of silica fume particles were finer than 1 µm. The typical physical properties of the silica fumes are given in Table 1.

Table 1:Properties of Silica Fume

Properties	Value
Particle Size	< 1µm
Specific-gravity	2.22
Surface Area	13,000-30,000 m^2/kg

2.1.5. Polypropylene Fiber

Polypropylene fiber used in the present study was ‘Recron 3S’ of Reliance Industries Limited. Figure 1 shows the Scanning Electroscope Microscope (SEM) view of the polypropylene fiber used. The properties of the fibers are given in Table 2.

Table 2: Properties of PP Fiber

Properties	Values
Diameter	20±5μm
Length	6 ± 1mm
Aspect ratio	300
Density	1.36-1.38
Colour	White
Type of fiber	Monofilament

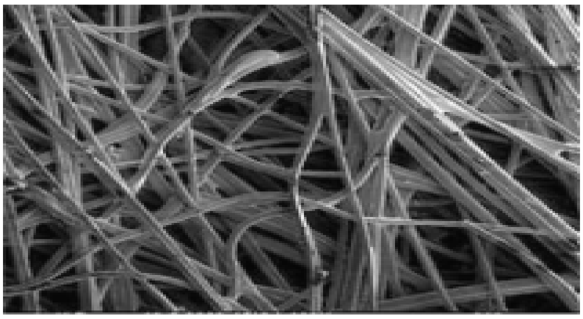

Figure 1: SEM View of PP Fiber

Structural Behaviour

The raw material of polypropylene is derived from monomeric C_3H_6 which is purely a hydrocarbon. Its mode of polymerization, its high molecular weight and the way it is processed into fibers combine to give polypropylene fibers the following useful properties:

- There is a tactic regular atomic arrangement in the polymer molecule as represented in Figure 2. Due to regular structure, it is known as isotactic polypropylene.

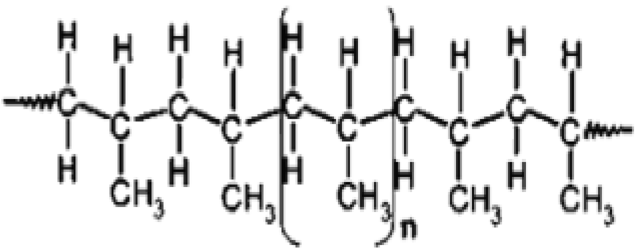

Figure 2: Monomeric Structure of PP Fiber

- The hydrophobic surface not being wet by cement paste helps to prevent chopped fibers from balling effect during mixing.
- Polypropylene is resistant to most of the radioactive chemicals. Any chemical that will not attack the concrete constituents will have no effect on the fiber either. On contact with more aggressive chemicals, the concrete will always deteriorate first.

2.2. Concrete Mix Proportions

Concrete mix design was done as per the IS 10262-2009 [21]. A total of nine mixes were prepared with varying percentages of fibers and silica fume with a target slump of 75-100mm. The percentages of polypropylene (PP)fibers and silica fume(SF) were varied as shown in the Tables 3, Table 4 and Table 5. The mixes were designated as Mix 1 (A, B, C), Mix 2 (A, B, C) and Mix 3 (A, B, C) depending on the percentage of polypropylene viz. 0.1%, 0.15% and 0.2% by volume of concrete respectively. Further, the mixes were subdivided into categories A, B and C based on the percentage of silica fume viz. 0, 0.05 and 0.11% by weight of cementitious material.

Table 3: MIX 1 (1A, 1B, 1C)

Designation	Water Cement Ratio	Percentage of Cement	Percentage Of Silica Fumes	Percentage of PP Fiber	Compressive Strength (N/mm^2)		
					7 days	14 Days	28 Days
MIX 1A	0.30	1	0	0.10	31	40	47
MIX 1B	0.30	0.95	0.05	0.10	32.5	40.5	48.5
MIX 1C	0.30	0.89	0.11	0.10	34	43	50.5

Table 4: MIX 2 (2A, 2B, 2C)

Designation	Water Cement Ratio	Percentage of Cement	Percentage of Silica Fumes	Percentage of PP Fiber	Compressive Strength (N/mm^2)		
					7 days	14 Days	28 Days
MIX 2A	0.35	1	0	0.15	31.5	42	45.5
MIX 2B	0.35	0.95	0.05	0.15	32.5	42.5	46.8
MIX 2C	0.35	0.89	0.11	0.15	33	43.5	49.5

Table 5: MIX 3 (3A, 3B, 3C).

Designation	Water Cement Ratio	Percentage of Cement	Percentage of Silica Fumes	Percentage of PP Fiber	Compressive Strength (N/mm2)		
					7 days	14 Days	28 Days
MIX 3A	0.40	1	0	0.20	29.5	45	52.5
MIX 3B	0.40	0.95	0.05	0.20	30.5	46.5	52
MIX 3C	0.40	0.89	0.11	0.20	31	46	54.5

2.3. Compressive Strength Testing of Concrete

Three specimens of each mix were tested to determine the average compressive strength. The dimension of the specimen was (150 x 150 x 150) mm conforming to IS 516-1959 [22].

2.4 Ultrasonic Pulse Velocity Test

An electro-acoustical transducer was held in contact with the surface of the concrete cube and acoustically-coupled using grease to generate longitudinal and shear stress waves which propagate through concrete. Calibrated receiving transducer was used to sense the generated waves and measure transit time. The view of the testing is shown in Figure. 3.

Figure 3: View of Ultrasonic Pulse Velocity Testing

Longitudinal pulse velocity, V is in km/s is obtained as per Eq.1

$$\boldsymbol{V = L/T} \tag{1}$$

V is the longitudinal of pulse velocity. L is the length of the path. T is the time taken by that pulse to traverse that path.

The UPV test was conducted as per the guidelines of IS 13311- Part1 [23]. The relation between the quality of concrete and the pulse velocity as per IS 13311- Part1 [23] is represented in Table 6.

Table 6: Quality of Concrete

Quality of Concrete	Pulse Velocity (km/s)
Excellent	>4.5
Good	3.5 to 4.5
Fail/Medium	3.0 to 3.5
Poor	<3.0

2.5 Resistivity Test of Concrete

Four-probe Wenner array resistivity meter was used to perform the resistivity test on concrete. Out of the four probes (Figure 4), the two outer probes are the insertion and removal points, whereas the two inner probes are the potential measurement points.

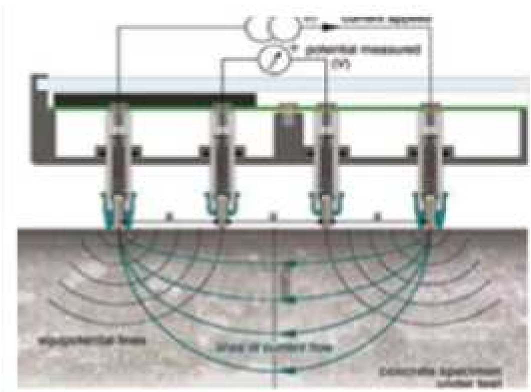

Figure 4: Schematic Representation of Four-probe Wenner Array Resistivity Meter Test

The probes were made to touch the external concrete surface, while an electronic control unit circulated the test current and measures the potential. The resistivity of concrete, ρ is obtained from Eq.2 [24]. WhereP is the difference in

potential between the measured points, a is the distance between the consecutive probes and I is the current when the probe is in contact with the face of body material.

$$\boldsymbol{\rho} = \mathbf{2\pi a} \times (\mathbf{P} \div \mathbf{I}) \quad \mathbf{(2)}$$

In practice, the probe is in contact with bodies of finite dimensions. When P’ and I’ are the potential and the current values obtained when the probe is applied to a finite body, the apparent value ρ', the resistivity (which is the value shown in the display screen of commercial probes) is given by:

$$\boldsymbol{\rho} = \mathbf{2\pi a}(\mathbf{P'} \div \mathbf{I'}) \quad \mathbf{(3)}$$

For smaller bodies such as the concrete cylinders, a cell constant correction K can be defined such that,

$$\boldsymbol{\rho} = \boldsymbol{\rho'}/\mathbf{K} \quad \mathbf{(4)}$$

Corrosion in concrete comprises of two stages. In the first stage the aggressive elements, such as chloride or carbon dioxide present in the surrounding medium penetrates into the concrete. The second stage is the propagation of these aggressive bodies in rather high concentrations at the reinforcement level. This corresponds to the rust growth, which can break the concrete, cover [25].

2.6 Permeability Testing of Concrete

Evaluation of the liquid and gas permeability in concrete was performed and consequent possible deterioration of the concrete was measured. Permeability was measured on hardened concrete cube specimens according to IS 3085-1965 [26].

2.6.1 Water Permeability Test on Hardened Concrete

A water pressure of 500 KPa for 48 hours was applied after placing the concrete cube specimen in the permeability testing apparatus. After applying the pressure for the specified time, the specimen was removed from the apparatus. The specimen was then split in half, perpendicularly to the face on which the water pressure was applied. As soon as the split face has dried to such an extent that the water penetration front can be clearly seen, the waterfront on the specimen was marked. The maximum depth of penetration under the test area was recorded to the nearest mm. Then using the test data water permeability coefficient was measured. To measure the coefficient of water permeability by flow, the Darcy’s Law (Eq. 5) was used [27]. The coefficient of water permeability, k is obtained as:

$$\mathbf{K} = \frac{\mathbf{QX}}{\mathbf{Ah}} \quad \mathbf{(5)}$$

where Q is the volume flow rate (m^3/s), A is the cross-sectional area of the test specimen, is the head of water and X is the specimen thickness in the direction of flow which is the depth of penetration.

2.6.2 Gas Permeability on Hardened Concrete

Gas permeability test was conducted using Permeability Test Rig (PTR). Concrete core samples of diameter 25 mm and lengths 75mm were drawn from the concrete cubes using an concrete cutter and trimming units. The test rig used to measure gas permeability. It is an apparatus which measures gas flow in core concrete and it has mainly three components:

- A confining pressure unit (bar), which is applied to core concrete at a given pressure;

- Pore pressure unit, which directly gives the pore pressure in 'psi' of a core concrete for a given confining pressure; and
- Gas flow rate, which directly gives the gas flow in 'Normal cubic centimeters per minutes' (Ncc/min) of a core concrete for a given confining pressure.

Finally, using gas permeability testing apparatus gas coefficient of permeability was measured directly by catalogue excel sheet which gives the value in 'mili-darcy'.

2.7. Shrinkage Testing on Concrete

Shrinkage test was carried out according to IS 13185-1991[28]. A thin polyethylene sheet was placed over the base to eliminate base friction between the concrete and mold. After mixing, the concrete was poured into the molds and exposed to a specific environment comprising of the constant temperature of 35°C and relative humidity of 75%. The cubes were then checked visually for any signs of cracking at the approximately 30-min interval for the next 24 hours [29,30].

3. RESULTS AND DISCUSSIONS

3.1. Compressive Strength

The variation in compressive strength for the various mixes are represented in from Figure 5 to Figure 7. Addition of silica fume and PP fibres has resulted in significant changes in the compressive strength of the mixes. The presence of silica fume in fiber reinforced concrete has eliminated the weak link by strengthening the cement paste-aggregate bond and forming a less porous and more homogenous microstructure in the interfacial region. Thus, PP Fiber reinforced silica fume concrete is stronger than conventional concrete, considering the exceeded strength of aggregate than that of the cement paste [31].

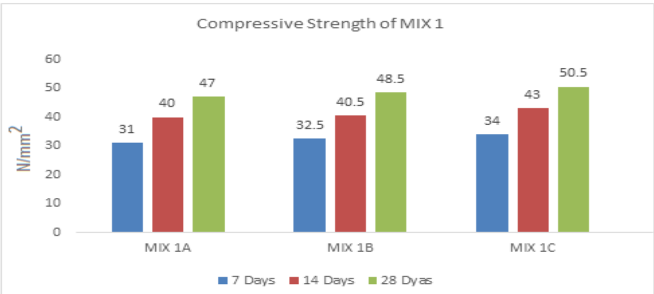

Figure 5: Variation in Compressive STRENGTH of MIX 1

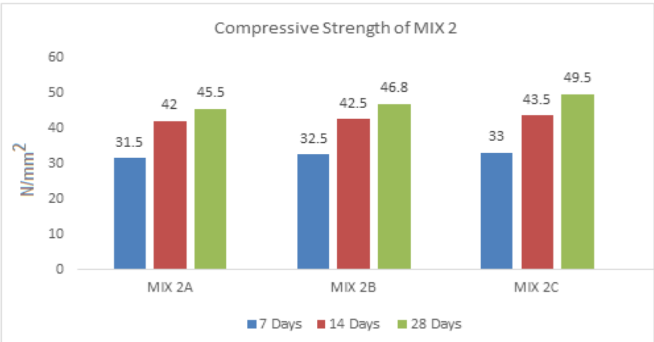

Figure 6: Variation in Compressive Strength of MIX 2

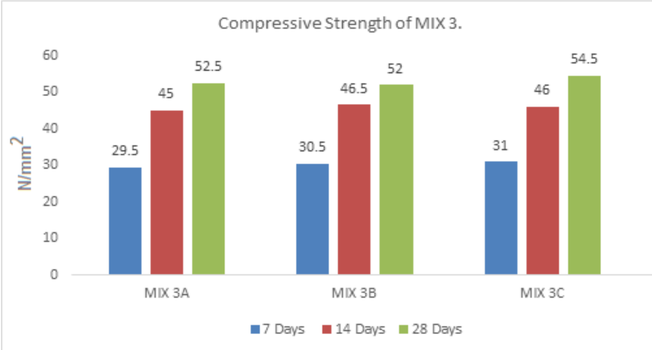

Figure 7: Variation in Compressive Strength of MIX 3

3.2. Ultrasonic Pulse Velocity Test (UPV)

Homogeneity of the fiber reinforced concrete measured by conducting the UPV test [23]. The variation in the pulse velocity readings is represented in Table 7 and Figure 8. The quality of concrete was found to be excellent at 28 days of age for all the mixes. Increase in pulse velocity was observed with an increase in fiber and silica fume content which ensured homogeneity of the concrete.

Table 7: Ratings of Ultrasonic Pulse Velocity Values for the Different Mixes

UPV Values	MIX 1			MIX 2			MIX 3		
	1A	1B	1C	2A	2B	2C	3A	3B	3C
7 Days	3.054	3.184	3.156	3.498	3.500	3.655	4.656	4.500	4.455
14 Days	4.500	4.750	4.890	4.900	4.910	4.990	5.260	5.654	5.800
28 Days	4.890	4.900	5.636	5.800	5.855	5.950	6.050	6.110	6.160

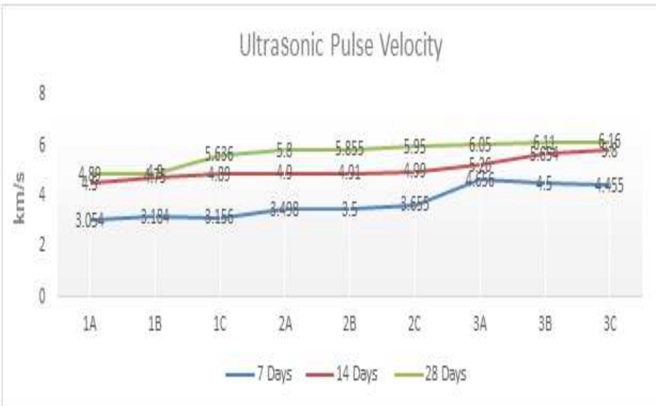

Figure 8: Variations in Ultrasonic Pulse Velocity Values

3.3. Resistivity Test

A brief evaluation of the influence in different proportions of silica fumes and type on the variability of the resistivity results were conducted. A total of 9 measurements were performed at the different concrete specimen, the concrete resistivity of the test specimen can be quickly determined with a four-point Wenner array probe and the application of a cell constant correction K. The value of K was computed as a function of the dimensions of the tested specimen and the inter-probe distance **a**. The optimum value of **ρ**inMixes 1C, 2C, 3C, shows better proportions Silica fumes with cementitious material. But the MIX 1C was possessed by the higher value of electrical resistivity due to the low water-cement ratio.

Table 8: Variability of Resistivity Readings for Different Mixes

Designation		ρ'(KΩ/cm)	Standard Deviation (S) of ρ'(KΩ/cm)	Coefficient of Variation $(S \div \rho') \times 100$	$\rho = \rho'/K$ (KΩ/cm)
Mix 1	**1A**	20.30	0.9	4.43%	13.6
	1B	32.33	2.2	6.80%	20.33
	1C	40.08	4.5	11.22%	**28.40**
Mix 2	**2A**	20.34	0.9	4.42%	13.7
	2B	33.00	2.2	6.66%	20.45
	2C	41.23	4.6	11.11%	**26.25**
Mix 3	**3A**	20.35	0.9	4.42%	13.7
	3B	33.31	2.2	6.60%	21.10
	3C	41.25	4.6	11.15%	**25.96**

3.4. PermeabilityTest

The water and gas permeability coefficients obtained by conducting the permeability tests on the concrete specimens are represented in Table 9. The expected water permeability coefficient of plain concrete according to IS 3085-1965 [25] is 5.94×10^{-12}molem^{-1}s^{-1}Pa^{-1}while with the addition of 0.2%PP fiber and 0.11% SF, an increase to 31.48×10^{-12}molem^{-1}s^{-1}Pa^{-1} (Mix 3C)was obtained. On the other hand, gas permeability coefficient was found to be 226.76×10^{-12}molem^{-1}s^{-1}Pa^{-1}(Mix 3C)for concrete with an addition of 0.2% PP fiber, against the minimum requirement of 39.98×10^{-10}molem^{-1}s^{-1}Pa^{-1}for plain concrete as per IS 3085-1965 [25]. Thus a factor of safety of 5 and 5.66 was observed for the MIX 3C in terms of water and gas permeability coefficients respectively. The view of water penetration front in concrete is shown in Fgure 9.

Figure 9: Water Front Penetration Depth on Divided Cube after Permeability Test

Table 9: Permeability Characteristics of PP Fiber Reinforced Concrete Mixes

Mix Designation		Gas and Water Permeability Coefficients	
		Water Permeability Coefficient (k_w x 10^{-12})mole m^{-1} s^{-1} Pa^{-1}	Gas Permeability Coefficient (k_w x 10^{-10}) molem^{-1} s^{-1}Pa^{-1}
MIX 1	**1A**	13.864	55.956
	1B	14.890	54.500
	1C	**15.640***	**57.492***
MIX 2	**2A**	25.015	79.263
	2B	26.111	86.120
	2C	**26.310***	**91.780***
MIX 3	**3A**	30.215	158.231
	3B	30.256	198.761
	3C	**31.480***	**226.760***

3.5. Shrinkage Test

The shrinkage crack pattern of the cubes of Mix 1C, 2C And 3C are represented in Figures 8,9 and 10 respectively. Measurement of cracks; comprising o the crack width (average) and percentage of the total crack area were displayed using an image analysis software named PAX-it. A small part of the surface of concrete cubes is snapped and processed in image analysis software.

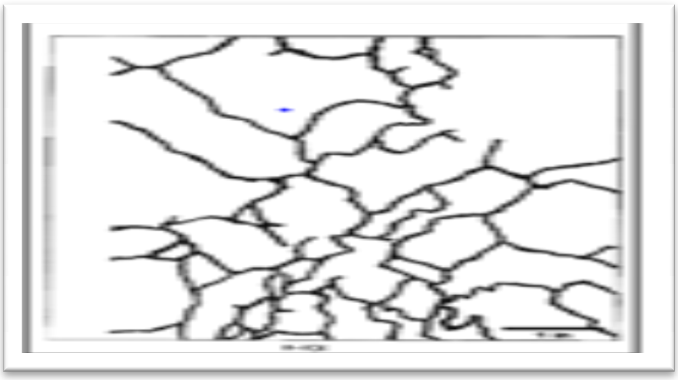

Figure 10: Shrinkage Crack of MIX 1C

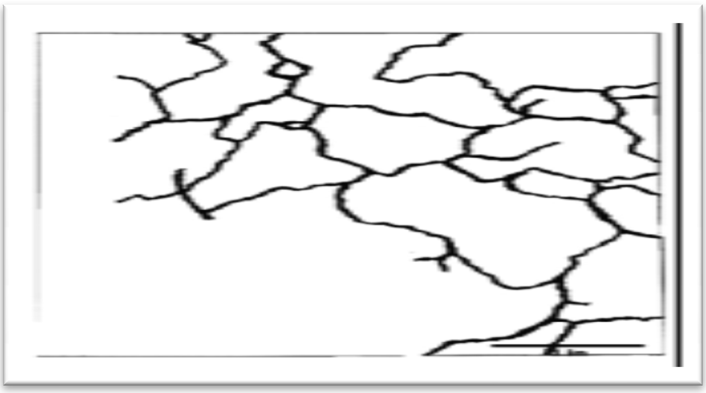

Figure 11: Shrinkage Crack of MIX 2C

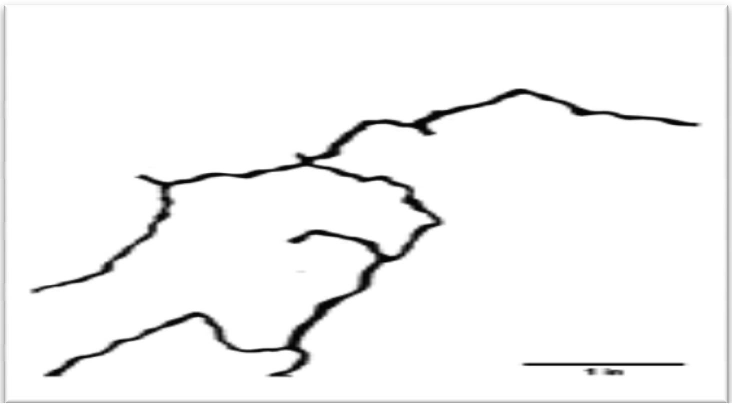

Figure 12: Shrinkage crack of MIX 3C

The shrinkage crack decreases with the addition of fiber as shown in Figures8, 9 and 10. The variations in the average crack area and crack width (mm) of the cubes are represented in Figure 11& 12 respectively. The crack width has reduced by 84% with the addition of PP fibers from 0.1% to 0.2% (with 0.11% SF).

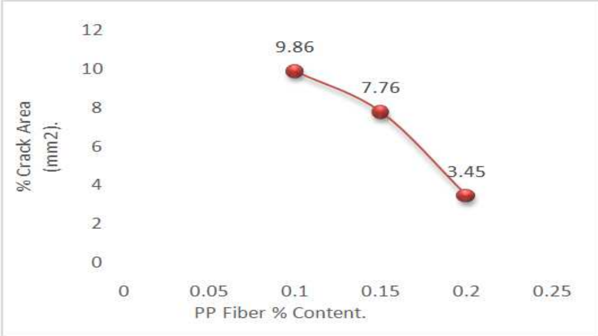

Figure 13: Variation of % of Crack Area (mm^2)

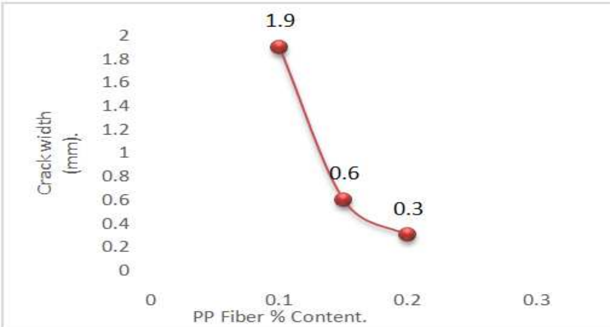

Figure 14: Variation of Crack Width (mm)

4. CONCLUSIONS

The experimental results indicated that at low fiber volume fraction, it is possible to obtain a material with enhanced strength, homogeneity and resistivity; and desired less permeability by using PP fibers and added silica fumes. The presence of silica fume in fiber reinforced concrete which strengthens the cement paste and aggregate bonding and forming a less porous and more homogenous microstructure in the interfacial region could be the reasons for the enhancement in strength and resistivity properties. The following conclusions can also be derived from the present study:

- A maximum increase of 15.95% in the compressive strength was observed for Mix 3C (0.2% PP fiber and 0.11% SF) when compared to that of mix 1A.
- The quality of concrete in terms of homogeneity was found to be excellent at 28 days of age for all the mixes. With a maximum quality index for the mix 3C (0.2% PP fiber and 0.11% SF)
- A factor of safety of 5 and 5.66 was observed for the MIX 3C in terms of water and gas permeability coefficients respectively which is very well suited for a nuclear waste container.
- A maximum of 84% reduction in shrinkage crack width the addition of PP fibers from 0.1% to 0.2% (with 0.11% SF) was observed.
- The electrical resistivity of concrete was not affected by the thickness of the material. Also, electrical resistivity was substantial; affected by the water-cement ratio and the percentage of silica fume as in MIX 1C (water-cement ratio: 0.30, % of Silica fumes: 11%)

With respect to the results of this study, it is understood that by using Polypropylene Fibre reinforced silica fume concrete possess favourable properties, which enables it to be considered as a viable option for storing nuclear wastes.

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